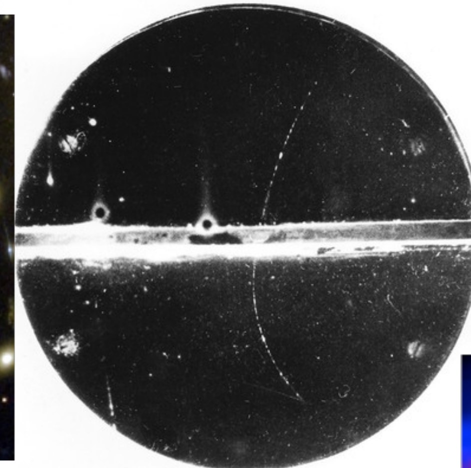
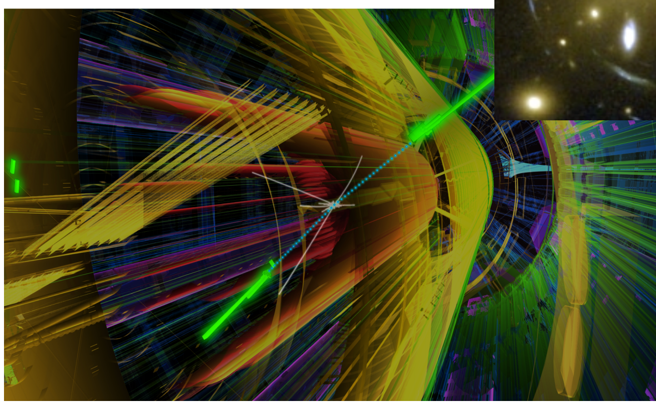
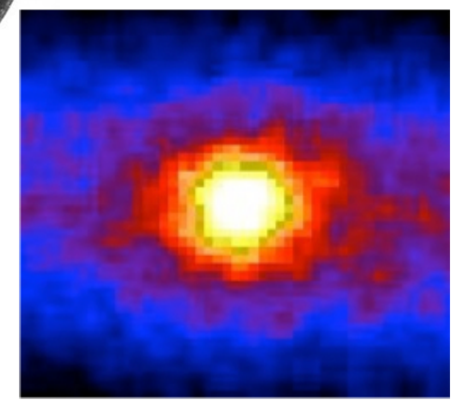
Exploration at the Energy Frontier





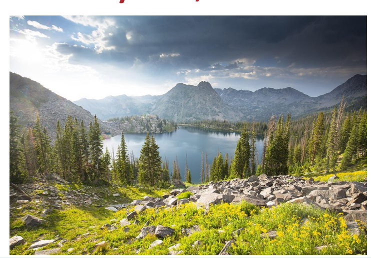


Marcela Carena

Fermilab/UChicago

Snowmass Energy Frontier Workshop - Open Questions and New Ideas

July 21, 2020



What does the Standard Model NOT explain?

What is dark matter made of and how does it interact with ordinary matter

Why there is more matter than antimatter left over from the Big Bang

What is the real nature of the Higgs; does it play a crucial role in explaining our existence

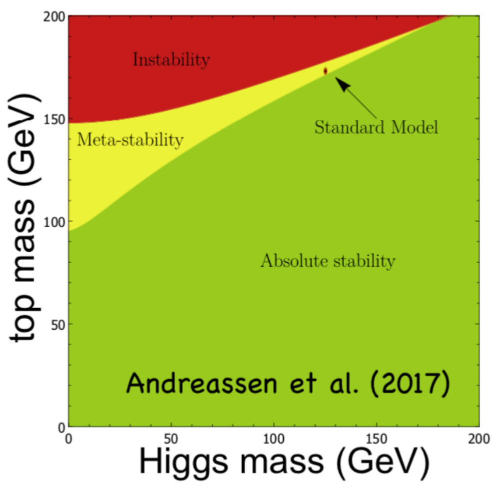
How do neutrinos get mass; do they play a prominent role in explaining our existence

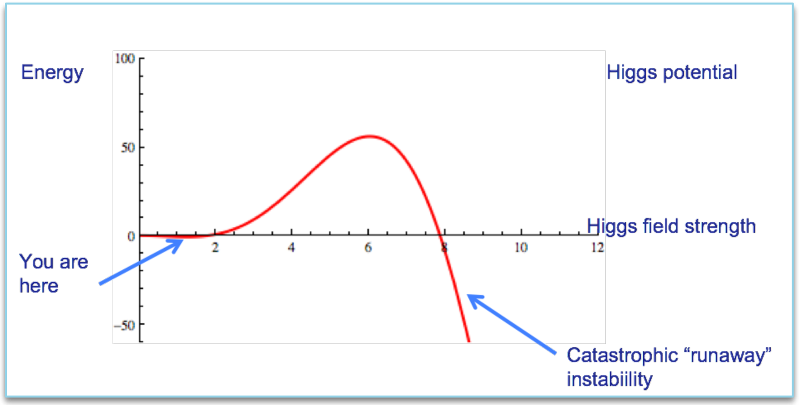
Why are the interactions of the Higgs tuned to make the quantum vacuum metastable

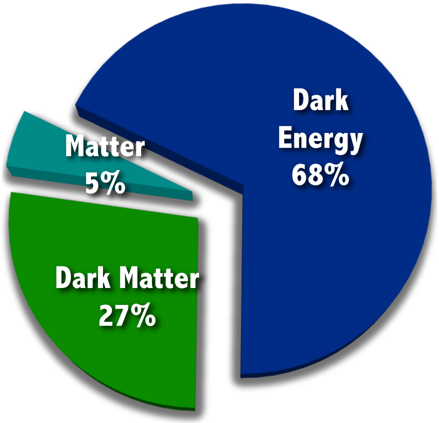
Why is $m_{top} \sim 3.5\ 10^5\ m_{e^-}$ (aka how do we explain fermion mass hierarchies)

What caused a period of cosmic inflation in the first instants of the Big Bang

What is dark energy







Energy Frontier Exploration

- should be guided/driven by the biggest mysteries in particle physics:
  - The existence of Dark Matter
  - The dominance of matter over antimatter

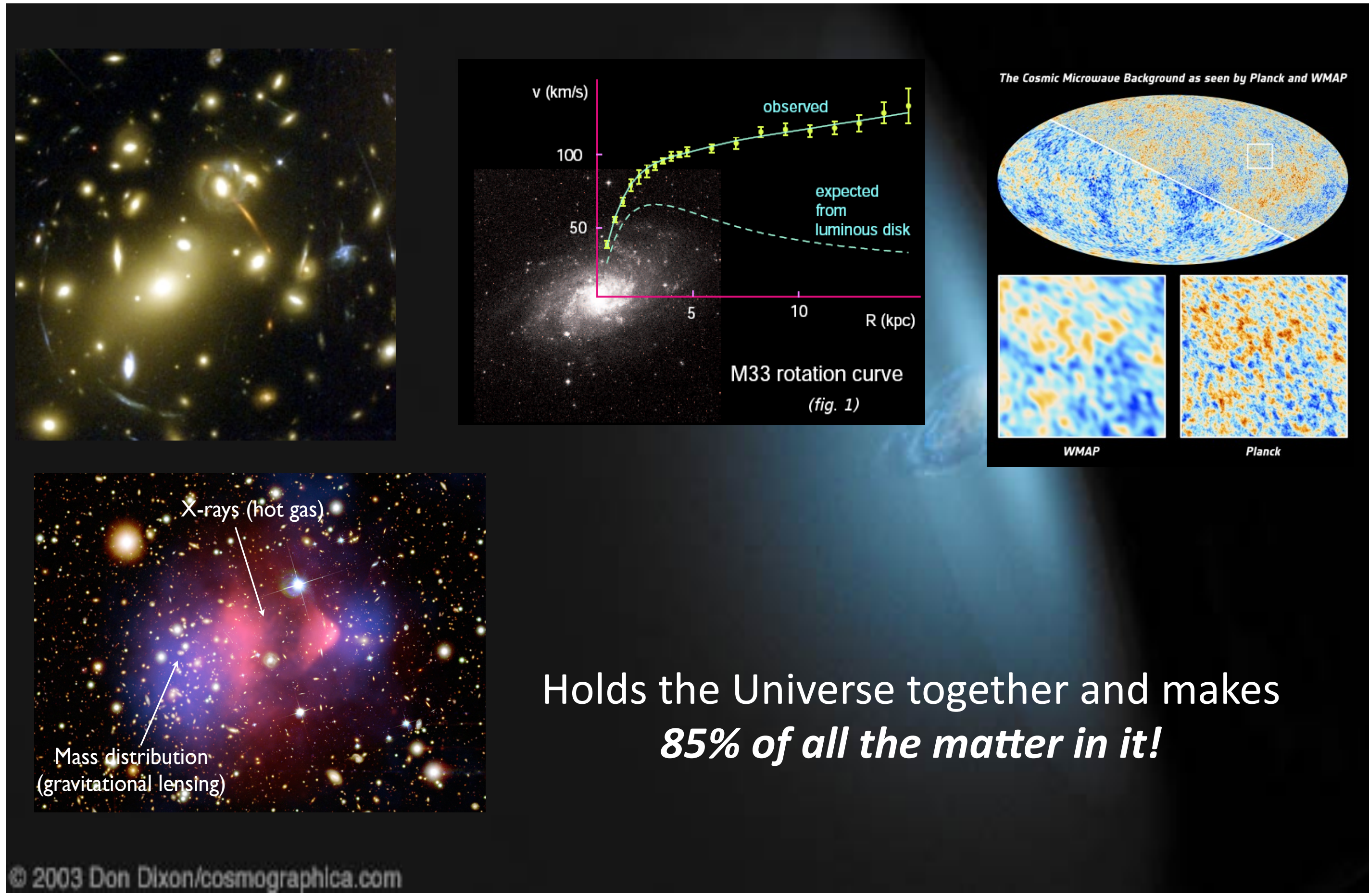
- should utilize our best tools for the exploration:
  - Visible particles and known interactions
  - Well understood mathematical structures

- should capitalize on the recent Higgs discovery to explore new ideas
  - New forces, new symmetries, new particles
  - Dark sectors and portals
  - Implications of the phase transition that occurred instants after the Big Bang

The search for physics Beyond the SM is the main driver of the exploration programme as stressed in the European Strategy Briefing book: https://arxiv.org/abs/1910.11775

Dark Matter

Compelling evidence from galactic and cosmological observations that DM exists, awaiting for discovery



Creating/Detecting DM in the laboratory is one of the greatest challenges

What do we know about Dark Matter ?

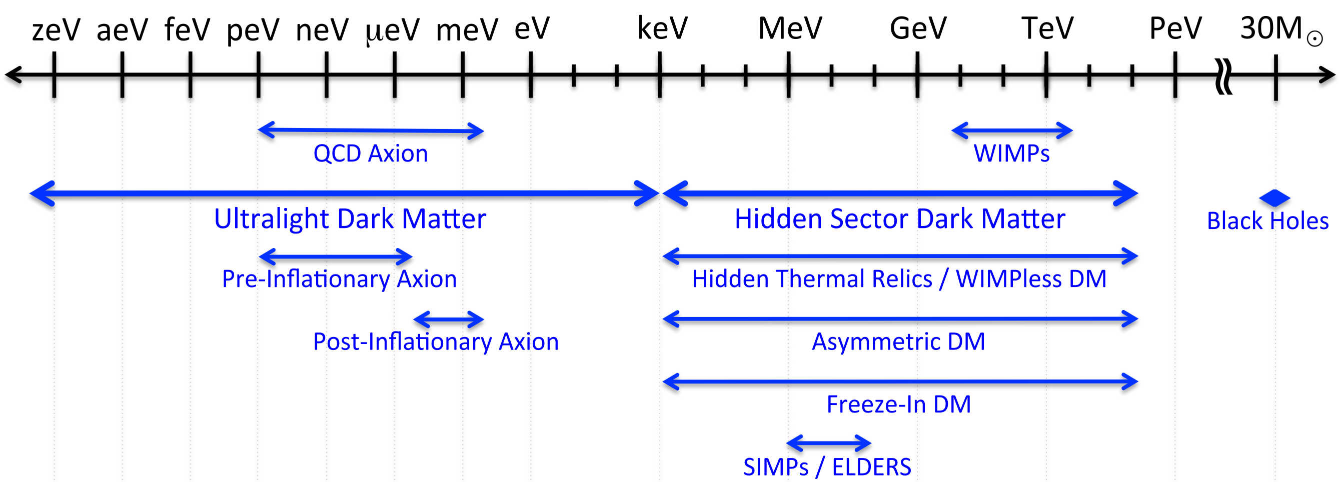
very little -

- Couples gravitationally
- It is the most abundant form of matter
- It can be part of an extended hidden, dark sector
- It can be made of particles or compact objects

  - ultralight DM is best described as wavelike disturbances (e.g axions) -

- Its mass can be anything from as light as 10^{-22} eV to as heavy as primordial black holes of tens of solar masses

Too small mass
⇒ won't "fit"
in a galaxy!



From
MACHOs
searches

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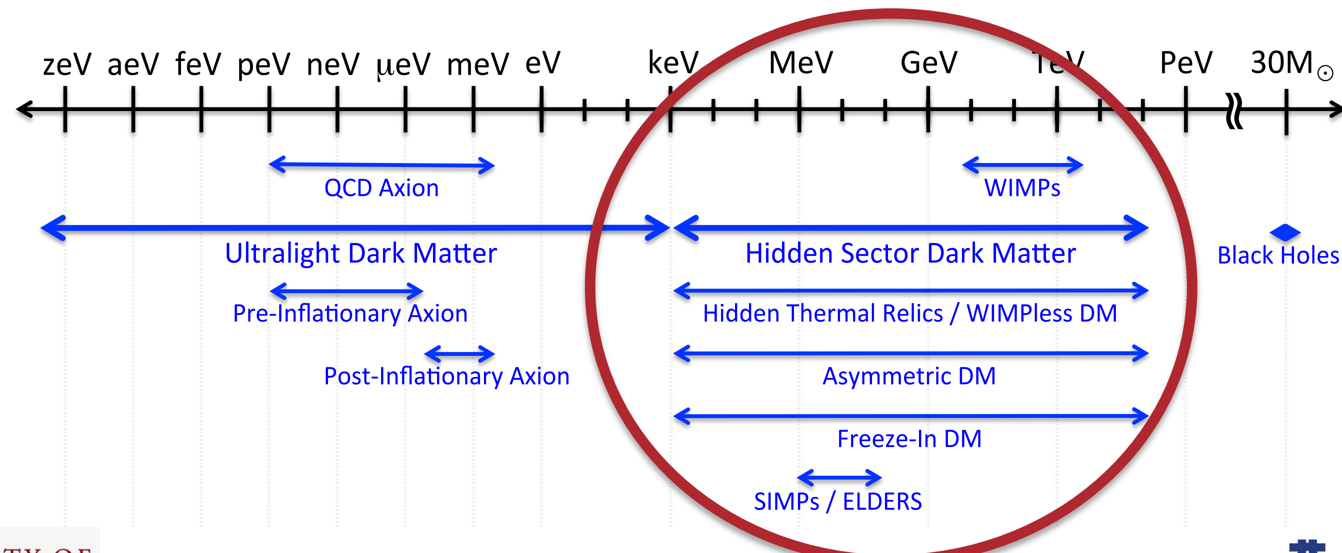

From
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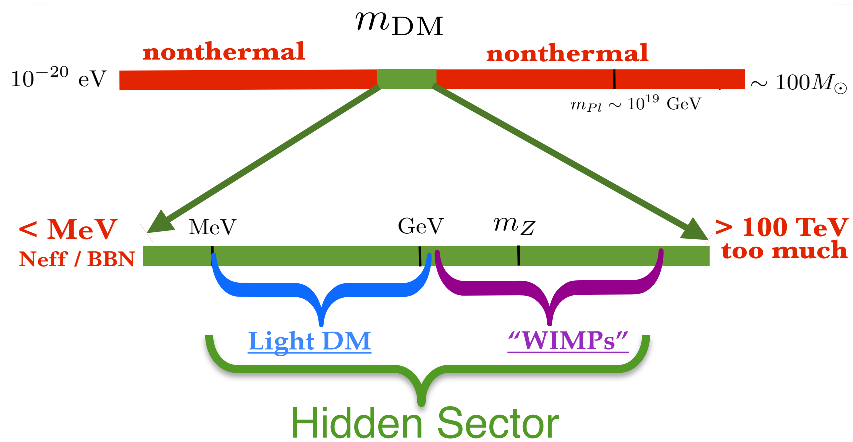
searches

What do we know about Dark Matter ?

very little -

- Assumptions about early Universe cosmology provides some guidance

Thermal Equilibrium in early Universe narrows the viable mass range

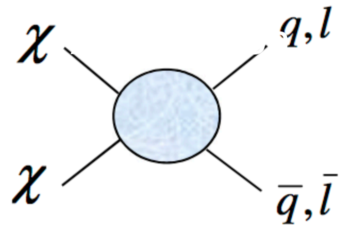


- It can have weak SM charges and be part of an extended SM sector
  ➔ Weakly Interacting Massive Particles **(WIMPs)**
- It can belong to a Hidden Sector & interact indirectly with SM particles via a Mediator
  The mediators may be SM singlets that mix/interact with SM particles (portals) such as the Higgs boson, the photon or neutrinos **or** they may directly carry SM charges
- It can have different type of properties with itself (e.g. collisionless, self interacting)

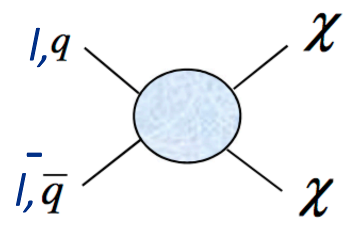
Explorable at accelerator-based DM searches: collider & fixed target/beam dump exp.

Phenomenology of low mass region [MeV-GeV] thermal DM is quite different from Standard WIMP ==> Demands light mediator/s that in themselves are a search target

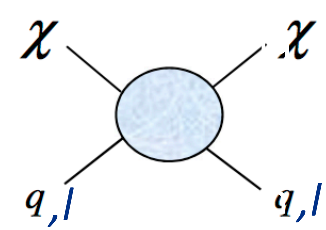
Dark Matter Detection Methods



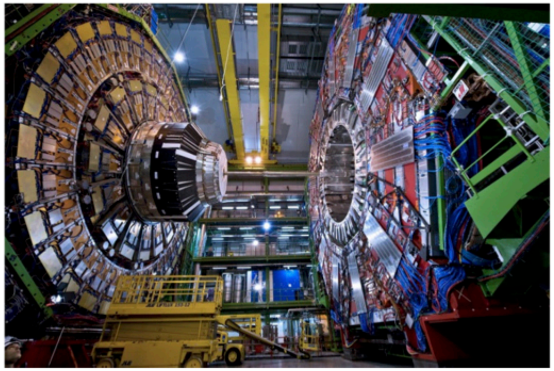
Above ground



Collider



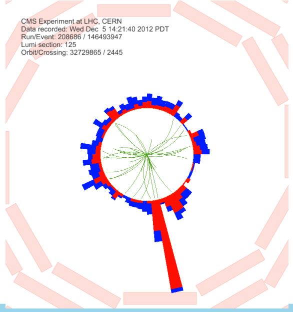
Underground



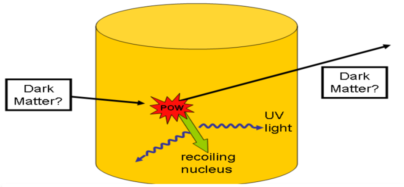
Thermal freeze out at early Universe, detect its annihilation products now:

gamma-rays, neutrinos and charged cosmic rays

Create DM at the Energy Frontier



It can collide with a single nucleus in the detector and be observed



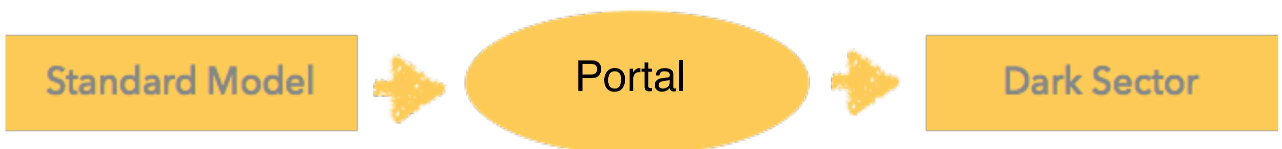
DM/Dark Sector Exploration at the Energy Frontier

- High-energy colliders could produce DM particles with masses and coupling strength as predicted by the thermal freeze out mechanism **in controlled conditions**.
- Main collider DM signature is the missing transverse momentum carried by the DM particle, otherwise invisible to detectors

  - if $m_{DM} < m_h/2$ and it couples to the Higgs ➔ effect in invisible Higgs decay width –

- Alternative signatures are the detection of mediator particles (whose exchange may be responsible for the annihilation processes that determine the DM abundance).

  - Mediators can lead to visible signatures but be only indirect evidence of DM
  - Mediators can be part of an extended Dark Sector



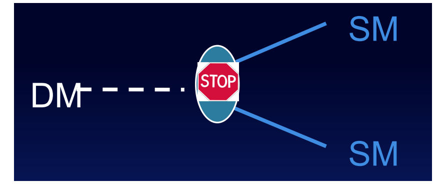
Dark Sector dynamics not fixed by SM
→ New Forces, New Symmetries and Multiple New States, including DM candidates

Interesting, distinctive phenomenology: Long-Lived Particles and Feebly Interacting Particles

Making DM at the LHC ?

Viable WIMP DM scenario: well known examples in **Supersymmetry**

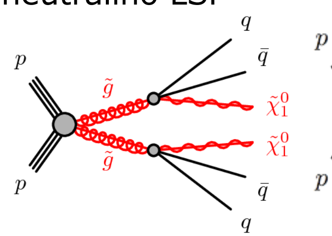
with additional R-Parity symmetry: $R_P = (-1)^{3B+L+2S}$

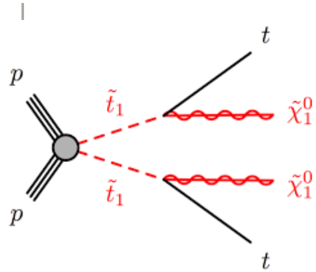


DM candidate is a mixture of fermionic supersymmetric-partners of the SM EW gauge bosons (gauginos: winos & binos) & extended Higgs sectors (higgsinos) ➔ **EWeakinos**

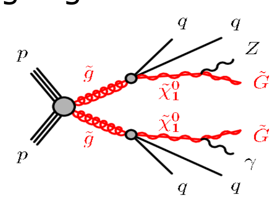
Can be produced @LHC in the decay of other SUSY particles (gluinos, squarks, Higgs, …)

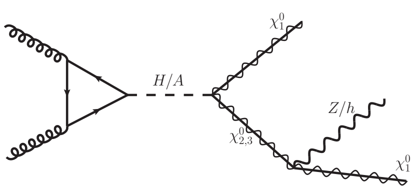
neutralino LSP



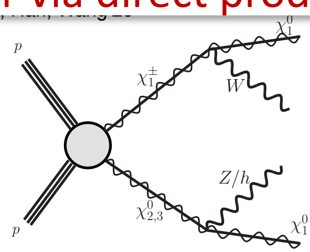


neutralino NLSP
light gravitino LSP

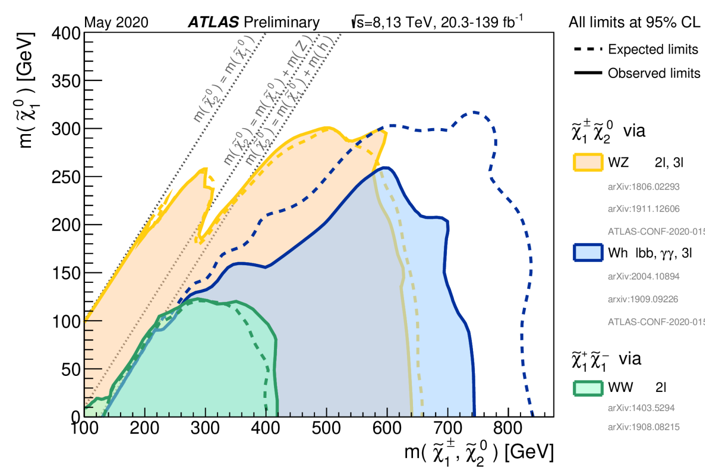




Or via direct production

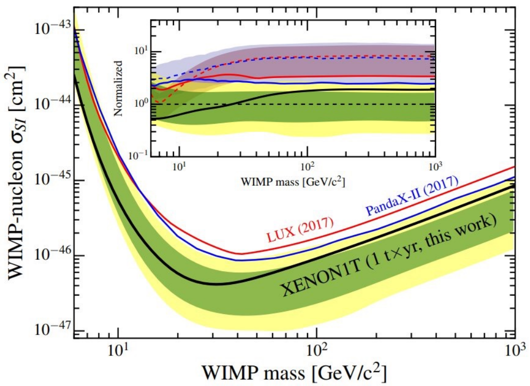


e. g. Wino-like searches at Run 2

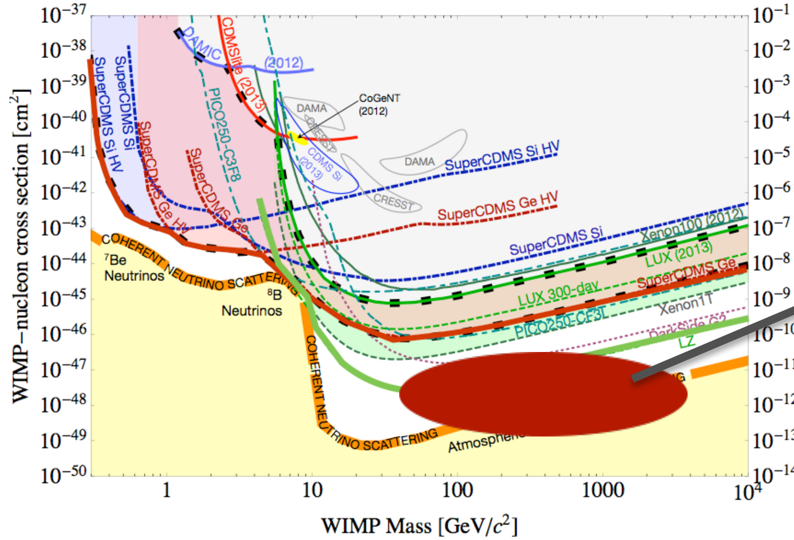


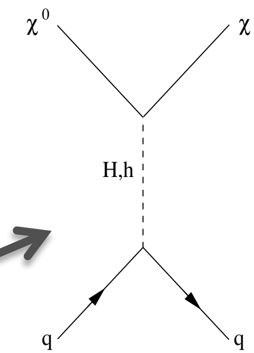
Caveat! Wino BR's assumed 1

Are the WIMP's dead? Direct Detection Blind Spots



Starting to probe the Higgs portal

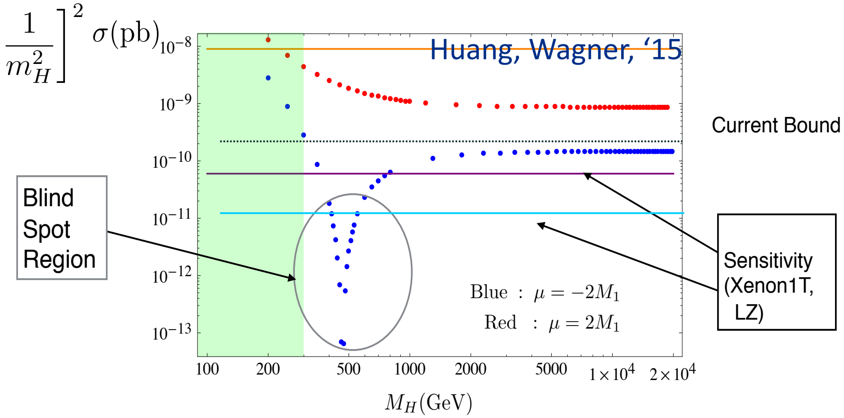




Close to Alignment (MSSM, mostly Bino LSP, Higgsino NLSP)

$$\sigma_p^{SI} \sim \left[(F_d^{(p)} + F_u^{(p)})(m_\chi + \mu \sin 2\beta)\frac{1}{m_h^2} + \mu \tan\beta \cos 2\beta(-F_d^{(p)} + F_u^{(p)}/\tan^2\beta)\frac{1}{m_H^2} \right]^2$$

$$\boxed{2\ (m_\chi + \mu \sin 2\beta)\frac{1}{m_h^2} \simeq -\ \mu \tan\beta \frac{1}{m_H^2}}$$



$m_{\chi^\pm} = |\mu|, \quad m_\chi^0 = M_1, \quad M_1 = 200$ GeV

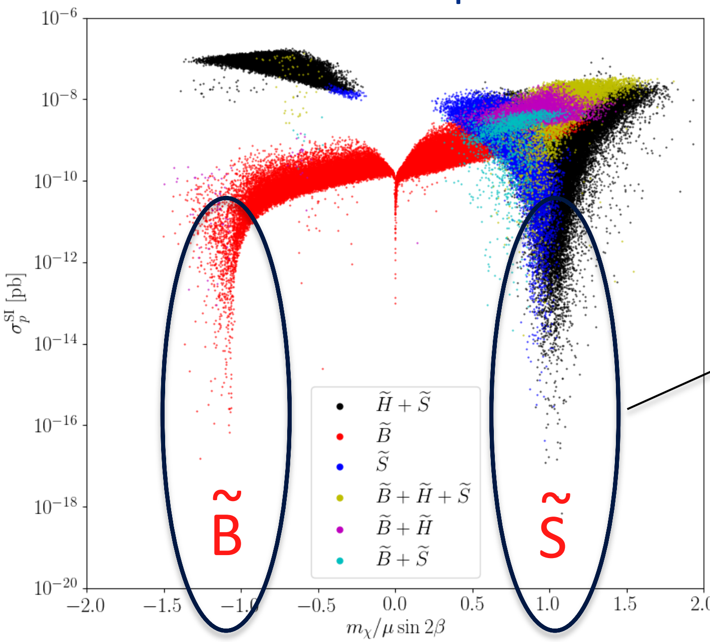
Destructive interference between h and H contributions for negative values of μ

Still room for a SUSY WIMP miracle

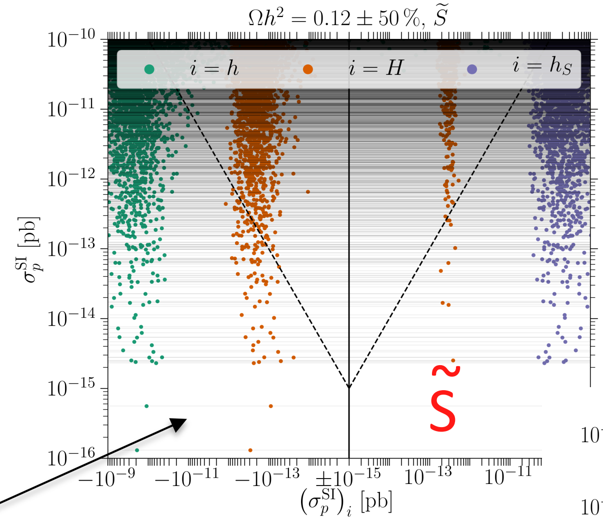
Direct Detection Blind Spots also in extended Higgs Sectors

Models with additional Higgs doublets **and singlets** plus fermionic dark matter opens up new possibilities: e.g. Singlet SUSY extensions of the SM

Blind Spots, hard to probe in Direct DM detection experiments



Baum, M.C. Shah, Wagner '18



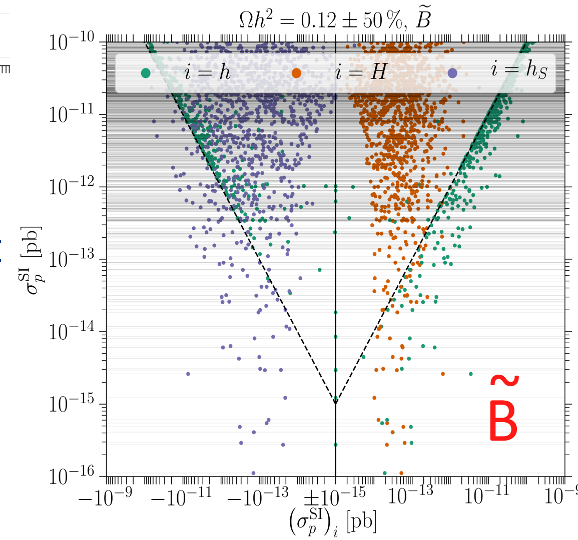
Mostly singlino DM

Three-way cancellation between the h_s, h and H contributions

Mostly bino DM

SM Higgs yields dominant contribution AND

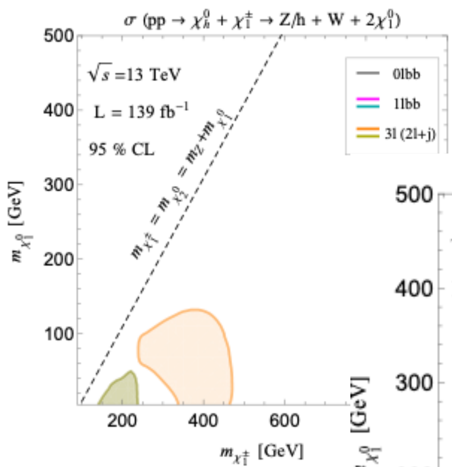
New Bino-Singlino well tempered region for relic density



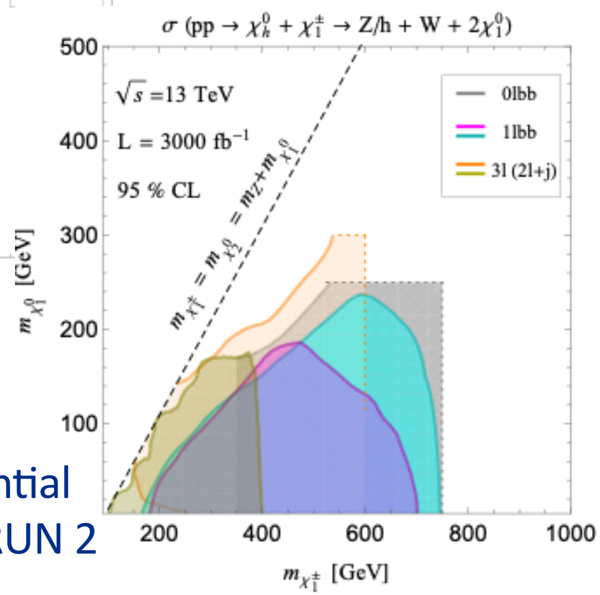
Yields observed DM thermal relic abundance and it could be observed at the LHC

WIMP Collider Reach: LHC, HL-LHC and Beyond

Bino-Higgsino HL-LHC sensitivity for $\mu < 0$, DD blind spot/smaller σ region



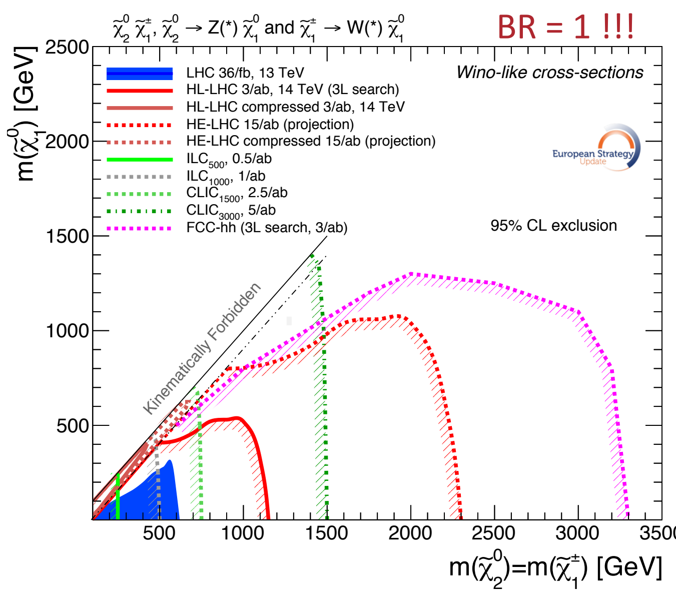
HL-LHC



HL-LHC has Discovery potential with respect to RUN 2

ATLAS recast by Liu, McGinnis, Wang, Wagner '20

Bino-Wino sensitivity at colliders (blind spot region still depend on Higgs sector interplay and μ)



- Compressed SUSY demands hadron colliders exploiting low-momentum leptons, recoiling against an ISR jet.
- Lepton colliders have reach up to kin. limit

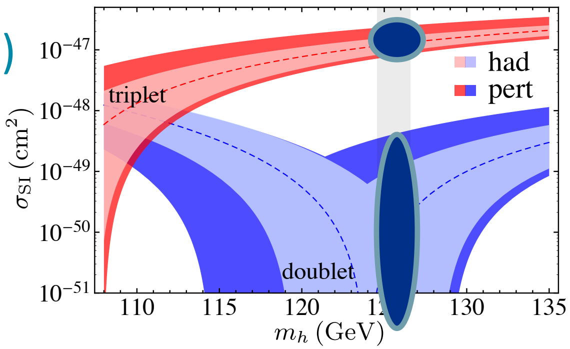
Coverage: Wino vs Higgsino NLSP ←→ larger vs smaller cross sections at LHC

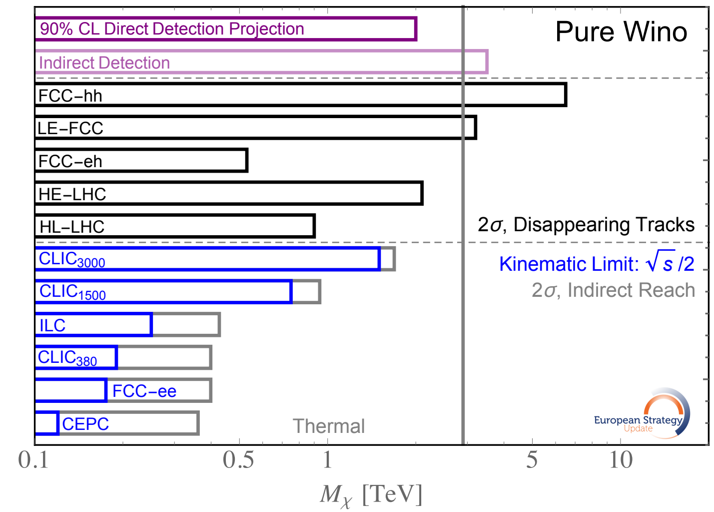
WIMP Standard Candles: Pure Wino or Higgsino DM

Being broadly probed by Direct and Indirect detection as well as Collider experiments

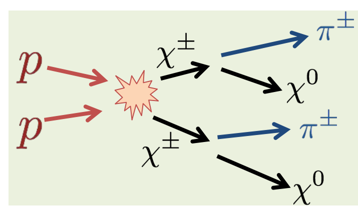
- Thermal abundance requires Wino (Higgsino) mass of about 2.9 (1.1) TeV

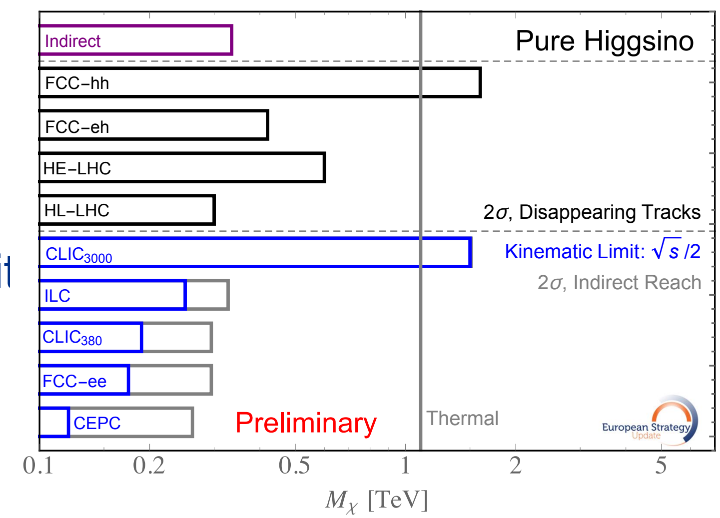
- DD: Wino (Higgsino) just above (deep into) the neutrino floor.





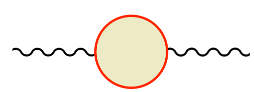
@ Hadron Colliders: Disappearing tracks





@ Lepton Colliders: Reach close to kinematic limit plus precision measurements extended reach

EweaKinos in loop modify propagators:



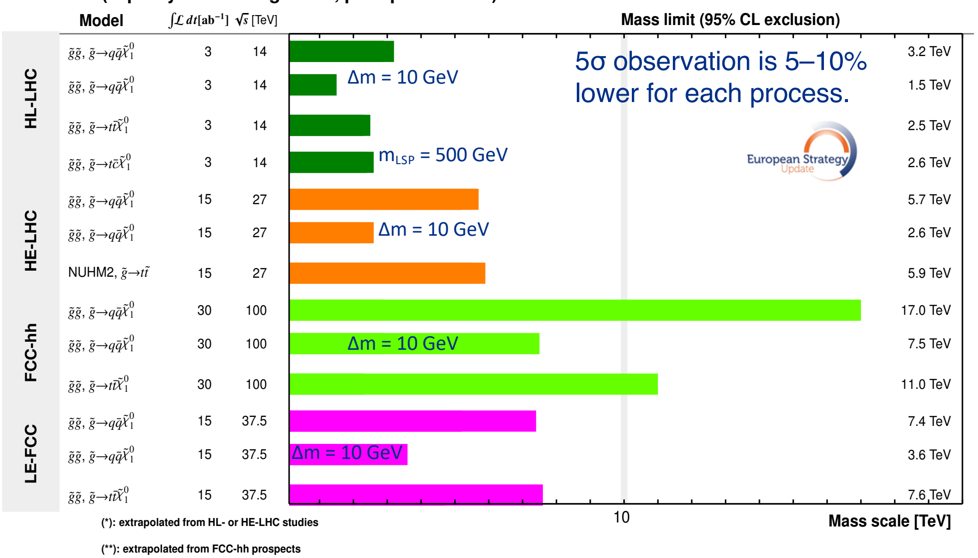
Exploring the Supersymmetric Zoo

If SUSY is there, we expect to observe new particles

Colored SUSY particles, squarks & gluinos, have the highest σ's at hadron colliders.

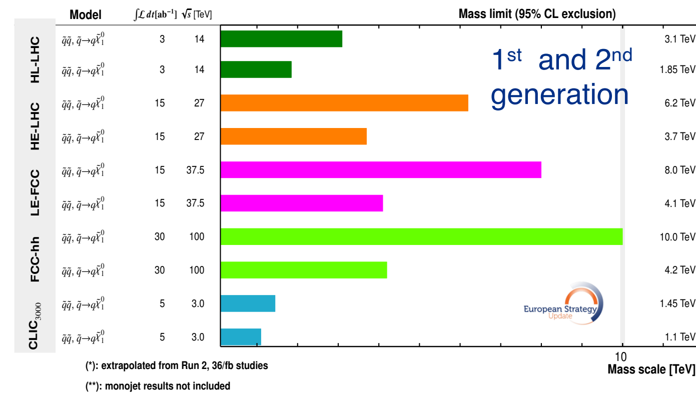
Hadron Colliders: gluino projections

(R-parity conserving SUSY, prompt searches)



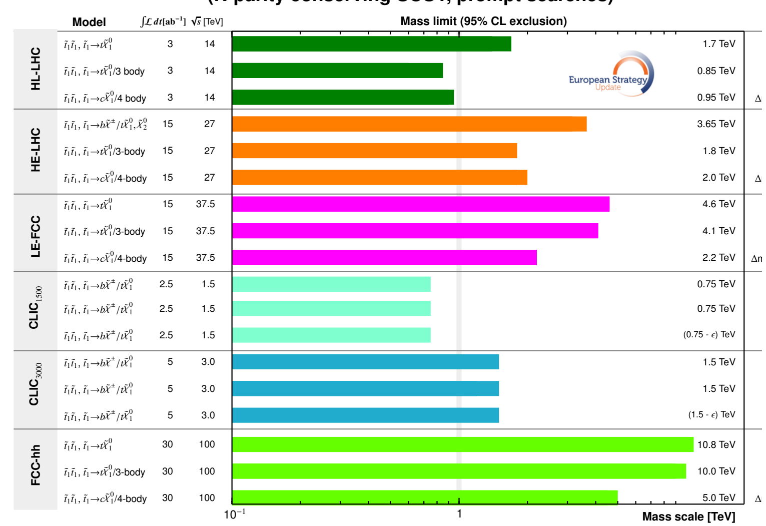
All Colliders: squark projections

(R-parity conserving SUSY, prompt searches)



All Colliders: Top squark projections

(R-parity conserving SUSY, prompt searches)



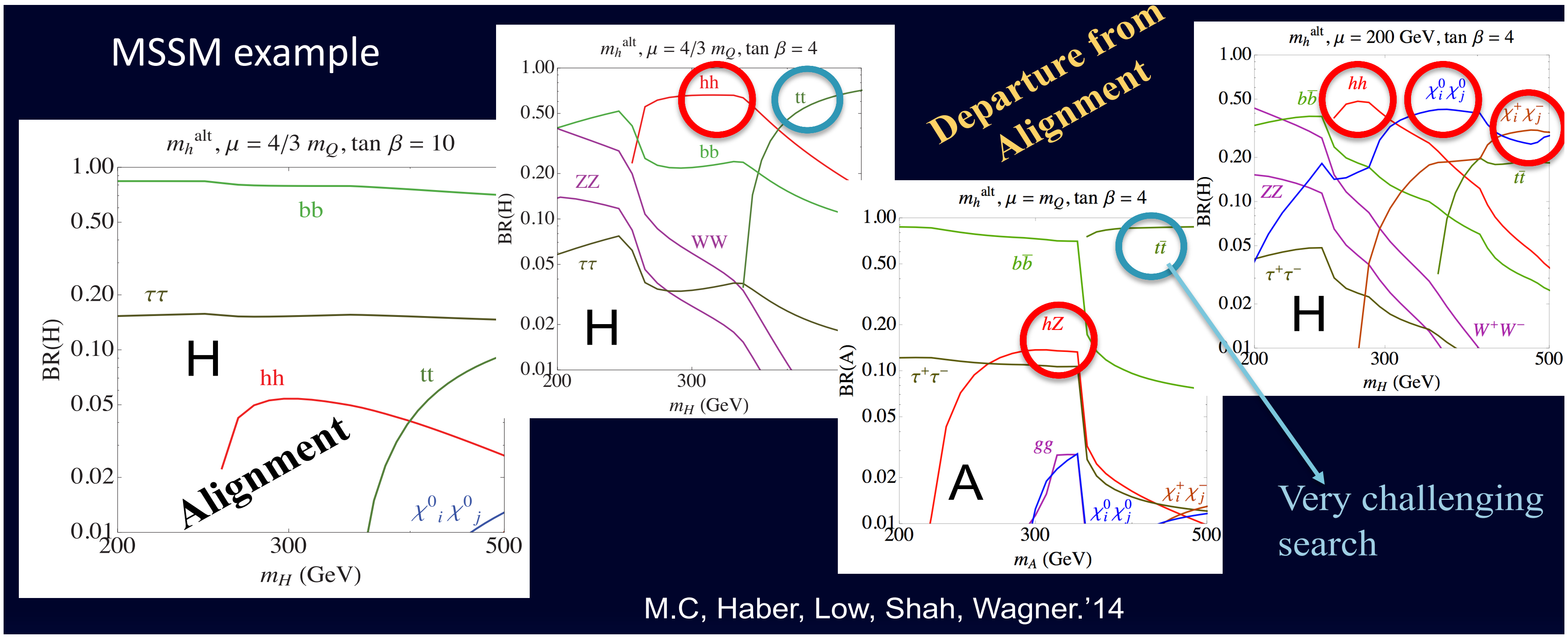
Future collider searches of gluinos and stops (in particular FCC-hh) will be powerful probes on the role of naturalness in the Higgs sector

Exploring extended Higgs sectors (in SUSY & beyond)

Additional Higgs Particles expected in most scenarios to explain what is not yet explain by the Standard Model

➔ SUSY and other BSM theories with clear signals at colliders and

additional Higgs Singlets: h_S, A_S, and Doublets: H, A, H^{+-}, some mixing with SM-like h



Dominant Higgs Decays into top pairs is specially challenging, since interference effects make hard to see signal - LHC is a top pair factory - MC and Zhen Liu '18

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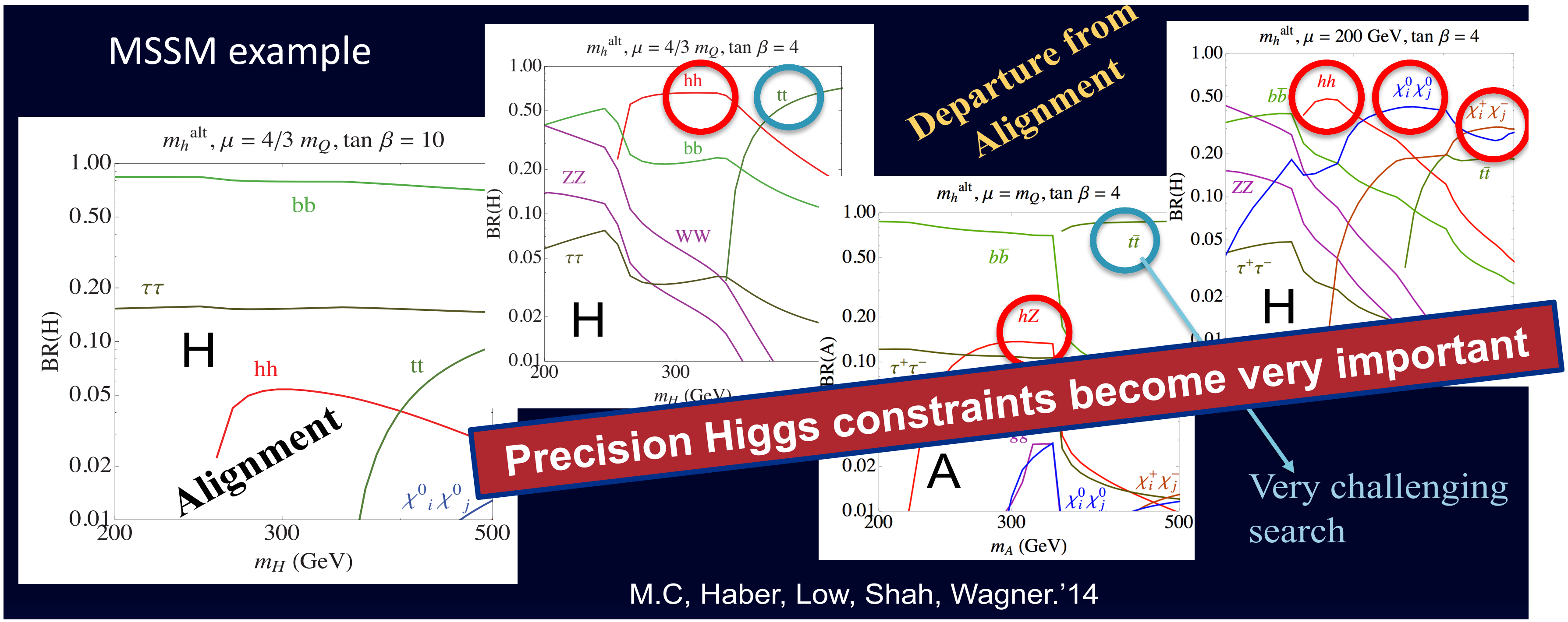

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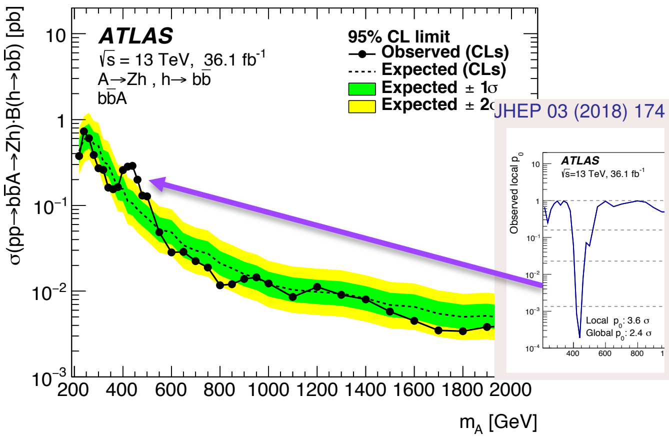
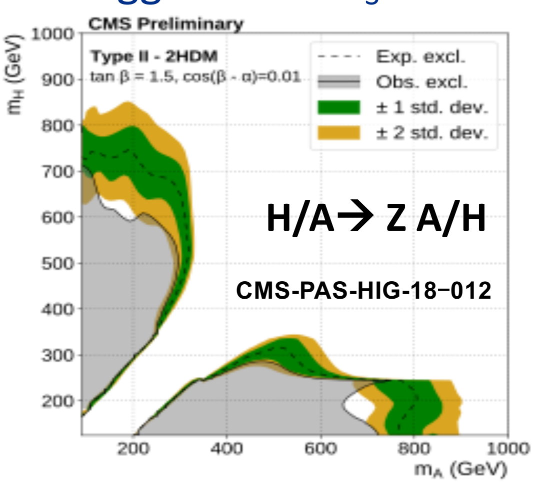
Higgs Searches in extended Higgs sectors

Now: ATLAS with A → Zh and h → bb

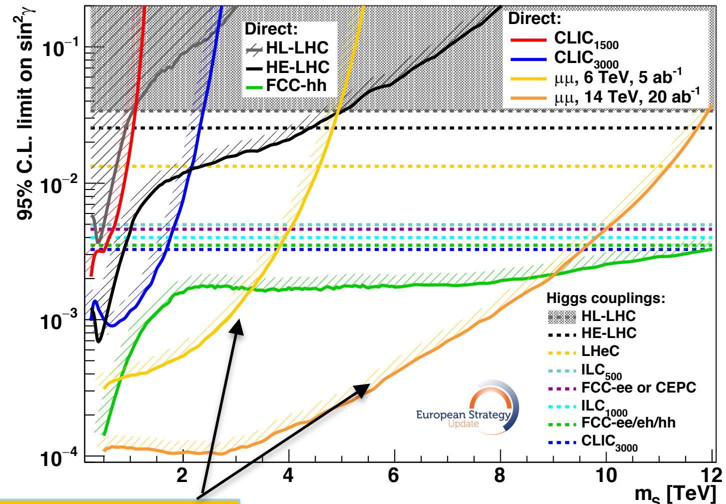


CMS gg → A → Z h_S → ll bb



complementarity to gg → h_S → WW

In the Future Energy Frontier

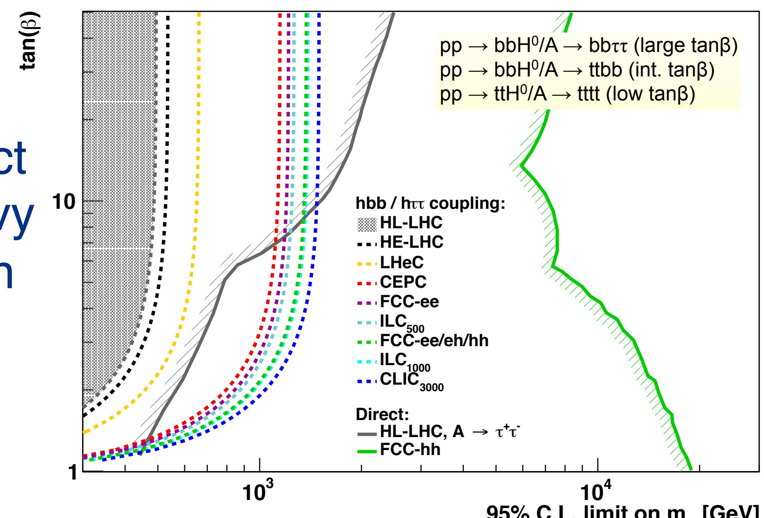


Scalar Singlet mixing with the SM Higgs

Direct reach @ FCC-hh better than precision H couplings for m_S < 12 TeV

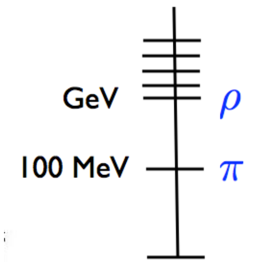
Muon Collider

Direct and indirect sensitivity to heavy neutral scalars in minimal SUSY.



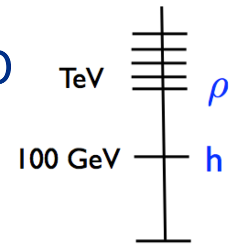
Higgs Boson itself could be a Composite Particle

Many BSM theories allow for composite Higgs Boson/s

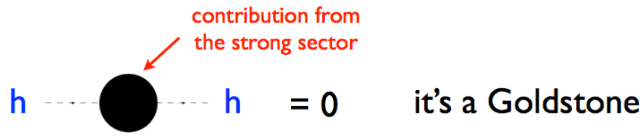


Inspired by pions in QCD

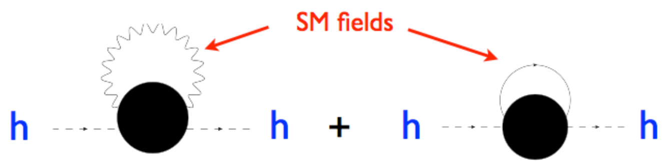
Higgs as a PNGB



Higgs is light because is a kind of pion of a new strongly interacting confining Composite Sector



Mass protected by the global symmetries

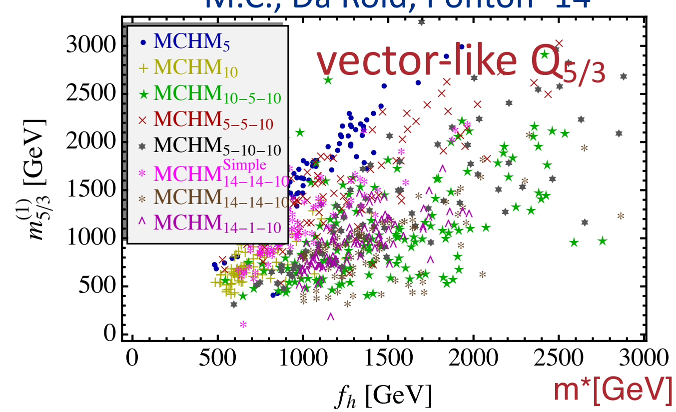


Mass generated at one loop: explicit breaking of global symmetry due to SM couplings

Composite-sector characterized by a coupling $g_* \gg g_{SM}$ and a confinement scale m_*

m_* controls the masses of the new vector-like fermion and gauge boson resonances

M.C., Da Rold, Ponton' 14

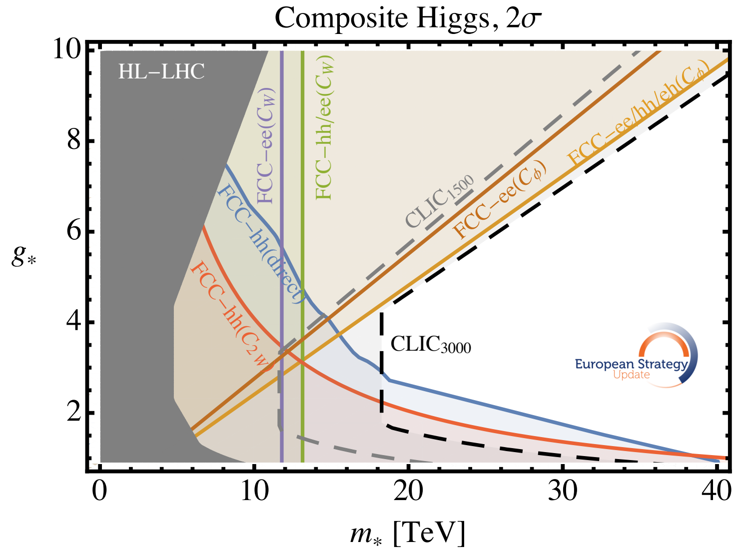


m_* sets the scale of EFT operators that describe at low energy the indirect effects of Higgs compositeness

Exclusion reach on EWSB and New Resonances

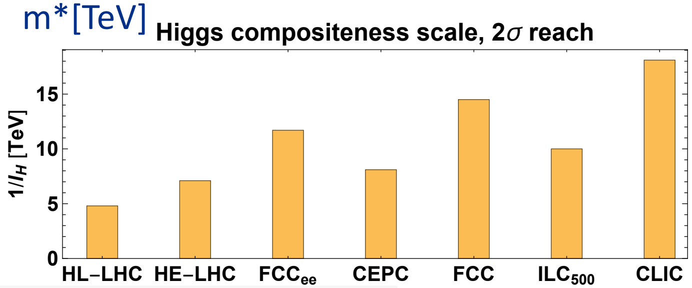
Reach on Composite Higgs Model Parameters

From probes of operators in the EFTCH and direct resonance searches



Higgs Compositeness scale, 2σ reach

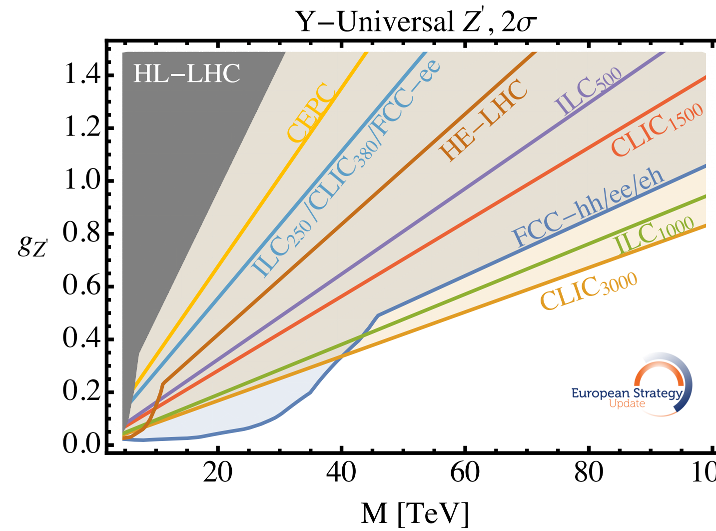
m*[TeV]



Test size of H up to inverse distances of order 10-20 TeV

Reach to New Vector Bosons

Representative Z' example with Hypercharge charges to SM particles And free parameter coupling g_Z'



Direct Z' searches overlaid with indirect sensitivity to the O_{2B} operator in the SM EFT

Back to Dark Sectors and Mediators

Mediators can come in many ways:

One can consider **Simplified Models**, e.g. simplest case only includes a Dark Sector with a Mediator and a DM candidate ==> four param models: m_{Med}, m_{DM}, g_{DM}, g_q (Med. Couplings)

Mediators can have masses larger or smaller than the DM candidate mass

Recall: If thinking about Light DM (sub GeV), and to achieve the observed relic density under standard cosmology assumptions ➔ a "light" mediator, singlet under SM gauge interactions

Mediators can decay to LDM or to SM particles through portal couplings

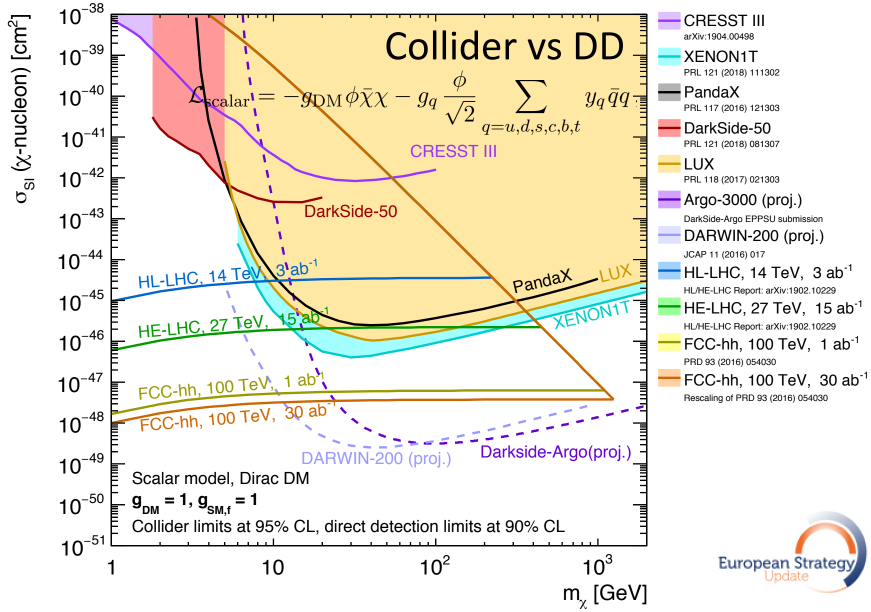
PBC report, arXiv:1901.09966

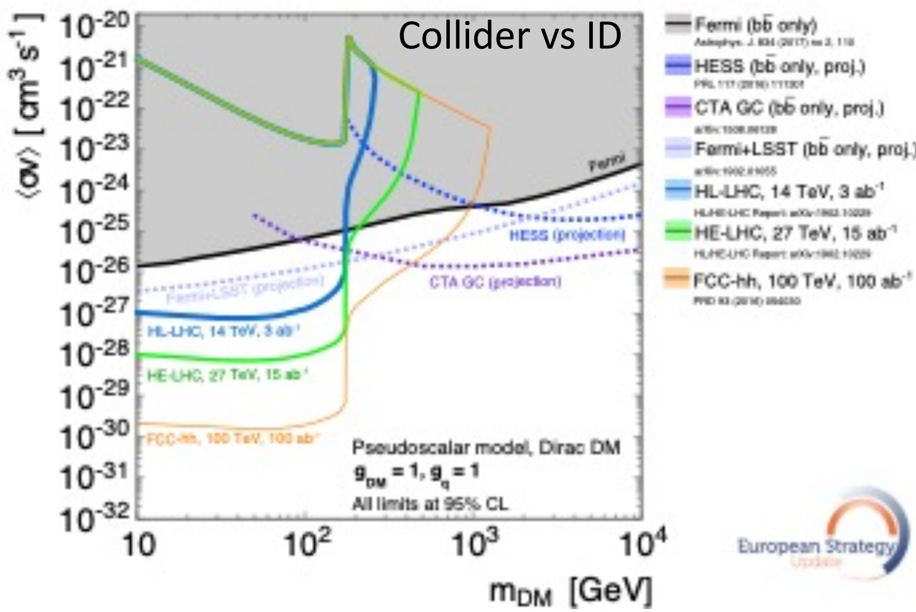
Portal	Coupling
Vector (Dark Photon, A_μ)	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Scalar (Dark Higgs, S)	$(\mu S + \lambda_{HS} S^2) H^\dagger H$
Fermion (Sterile Neutrino, N)	$y_N LHN$
Pseudo-scalar (Axion, a)	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$

Feebly Interacting Particles are of interest in their own and its presence has been large unexplored experimentally

Simplified DM-Mediator Models

Simplified models are useful toy models to compare the reach of Colliders* with that of Direct Detection and Indirect Detection experiments (many caveats!) arXiv:1603.04156





Future collider exp. are well suited to explore mediator models decaying to LDM candidates, as well as possibly reaching m_{DM} up to a TeV from decays of multi-TeV- mass mediators.

Good complementarity in the 10 GeV and 1 TeV mass range ==> could shed light on the nature of a DM candidate at reach in the next decades.

*LHC limits hold exclusively for the mediator under investigation and the specific choices of the couplings

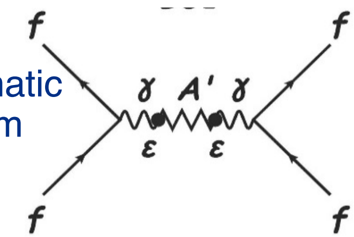
If a vel.-av. annih. σ value is obtained from a Med.-DM mass pair reachable by LHC, that σ value considered at LHC reach

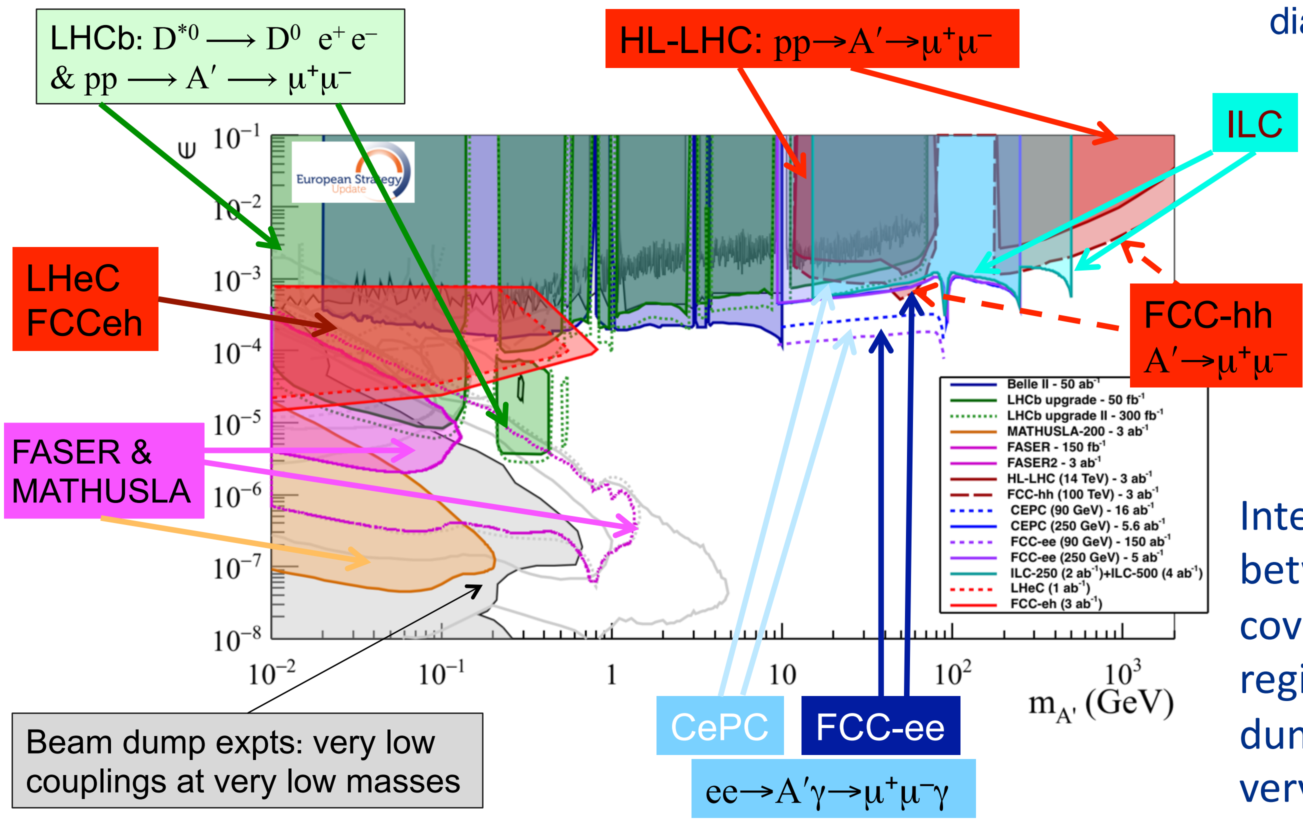
Feebly Interacting Particles at Accelerator-based experiments

Portals allow to identify common grounds to compare many machines/experiments

Dark Photon Portal: visible decays

Schematic diagram





HL-LHC, ILC(250+500), CEPC FCC-ee, FCC-eh, FCC-hh, have unique coverage in the high-mass range (> 10 GeV) down to ε ~ 10^{-4}

Interesting complementarity between future collider exp., covering high mass/large coupling regime, and FASER* plus beam-dump exp., covering low-mass, very low coupling regime.

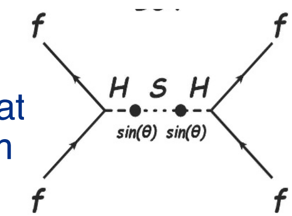
*Faser2 can be part of a **new facility** (cavern for Forward Physics Facility) opening new opportunities for LLP, DM, Dark Sectors, Neutrinos and more

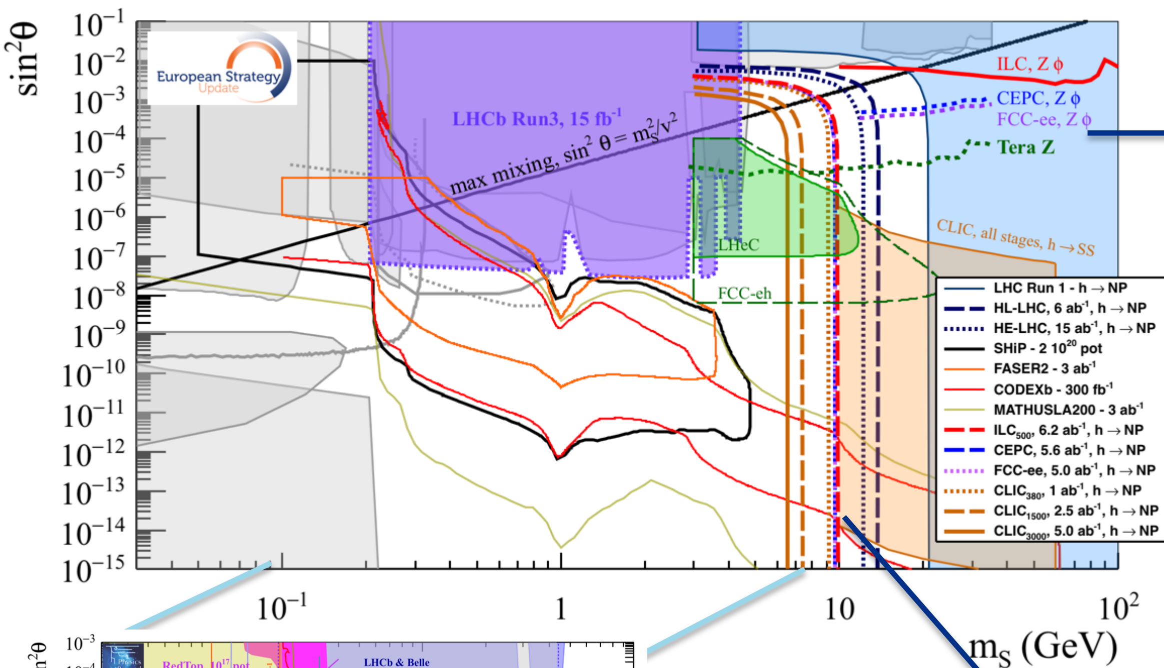
Feebly Interacting Particles at Accelerator-based experiments

Portals allow to identify common grounds to compare many machines/experiments

Dark Higgs Portal ($m_S > m_{DM}$; secluded annih.)

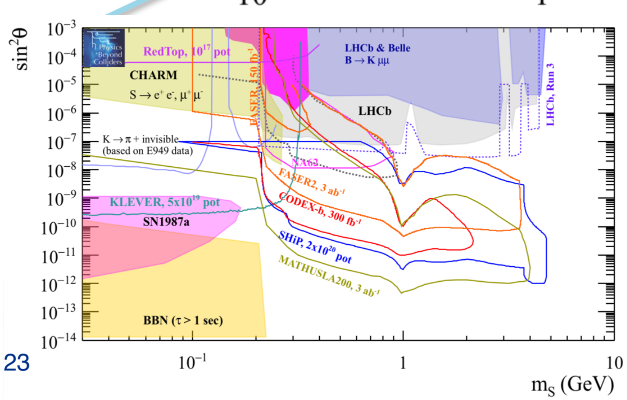
Schemat diagram





e+e- colliders using recoil ($e^+e^- \rightarrow ZS$) or running at Z -pole ($e^+e^- \rightarrow Z \rightarrow S\, l^{+l-}$)

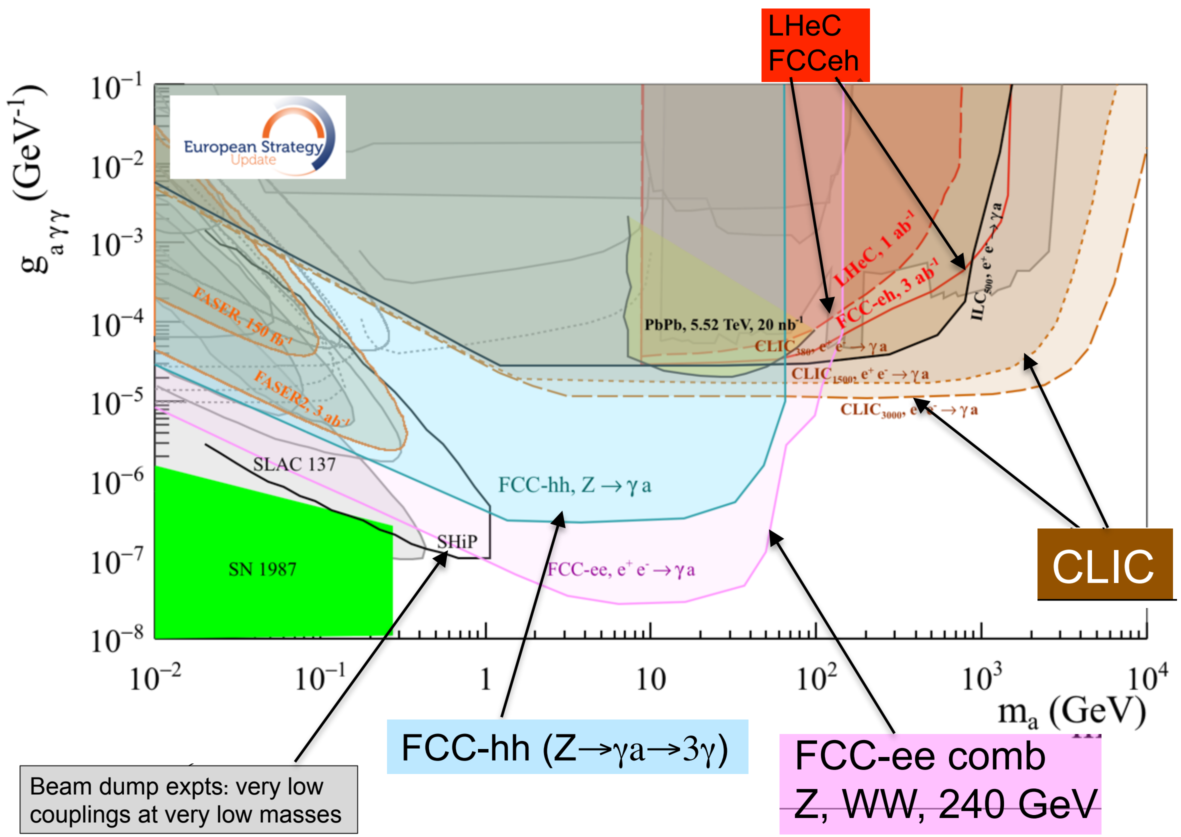
Bound Higgs/dark Higgs coupling from Higgs invisible width



Feebly Interacting Particles at Accelerator-based experiments

Portals allow to identify common grounds to compare many machines/experiments

Pseudo Scalar Portal (Axions, ALPS)



Main production processes at colliders:

e+e− → (*Z*) → *aγ*→*γγγ* (LC)
DY production with *Z* → *aγ* (HC)

Three mass regions:

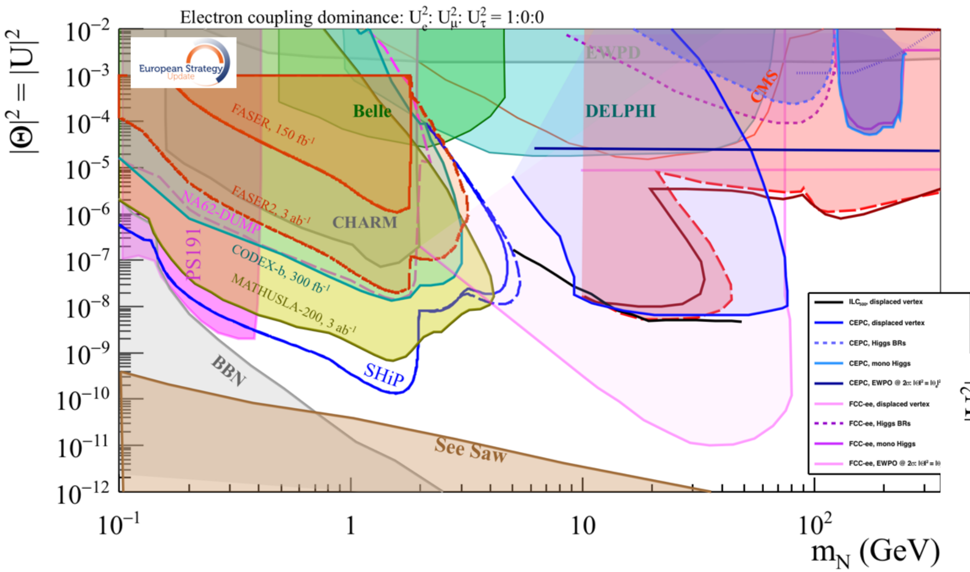
- m_a< 1 GeV → Faser and BD
- 1GeV < m_a< 90 GeV → leptons colliders at Z pole and HC via Z decays
- m_a = 10's GeV – few TeV at *e+e−* and pe colliders

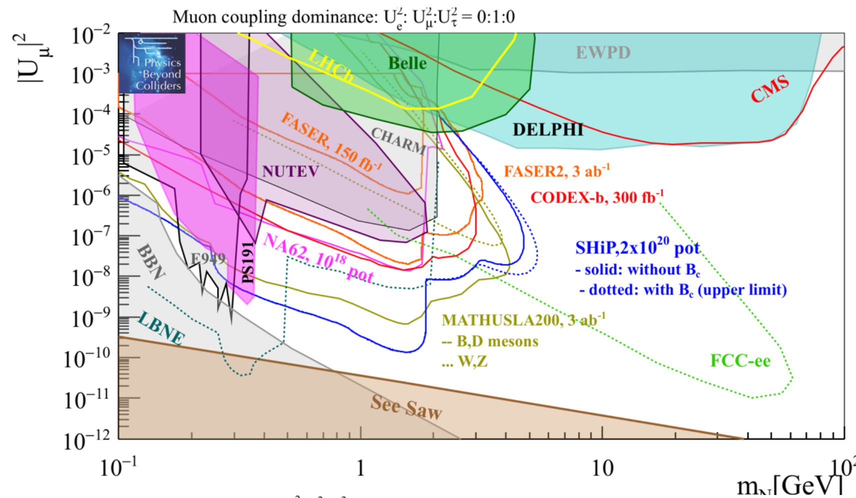
Future colliders can also search for ALPs with fermion & gluon couplings

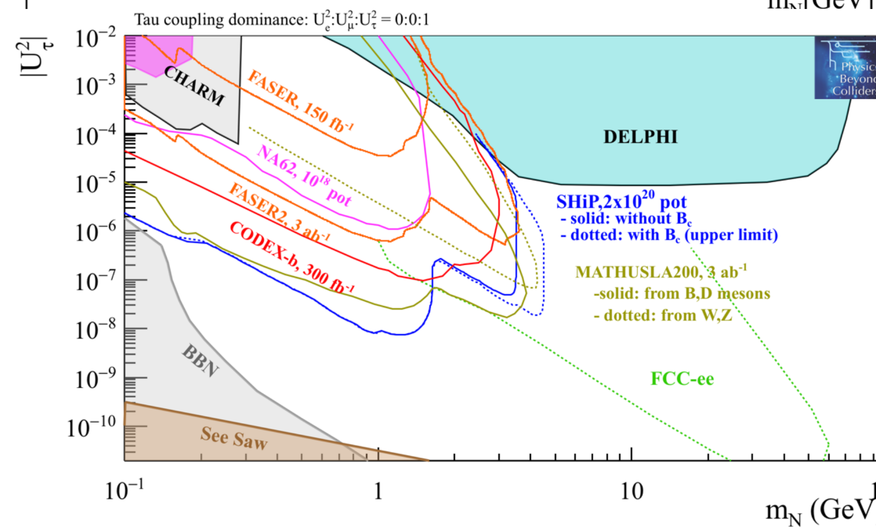
Feebly Interacting Particles at Accelerator-based experiments

Portals allow to identify common grounds to compare many machines/experiments

Heavy Neutrino Portal







Complementarity between, lepton colliders, Faser/Mathusla /Codexb and Beam Dump exp.

The Mystery of our Asymmetric Universe

Precision Cosmology:

Abundance of primordial elements, Predictions from Big Bang Nucleosynthesis and CMB

➔ information on baryon abundance: $\boxed{\eta = n_B / n_\gamma \approx 6.10^{-10}}$

What generated the small observed baryon--antibaryon asymmetry ?

Initial condition, or generated during the evolution of the universe?

Baryons, antibaryons and photons equally abundant in the early universe

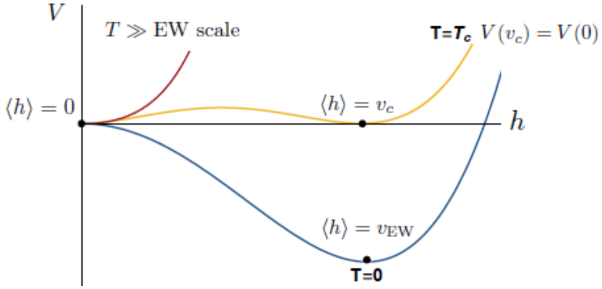
Starting from a CPT conserving theory, the necessary three Sakharov's conditions for baryogenesis are (Sakharov 1962)

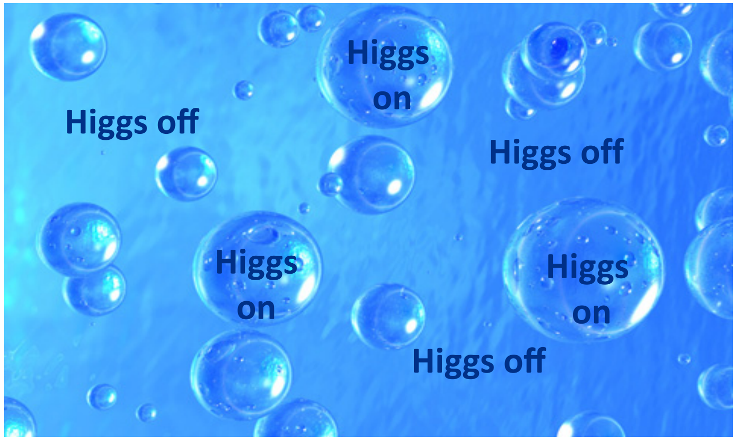
- Baryon (or Lepton) number violation: if universe starts symmetric
- C and CP violation: treat baryon/anti-baryon differently (to remove antimatter)
- Out-of-thermal equilibrium: suppress inverse processes

Possibilities: GUT Baryogenesis, Leptogenesis, **EW Baryogenesis** and more

Baryon Number generation at the EW phase transition

- Start with B=L=0 at T>Tc
- In a first order EW phase transition, universe tunnels from h = 0 to h≠0 vacuum via bubble nucleation.

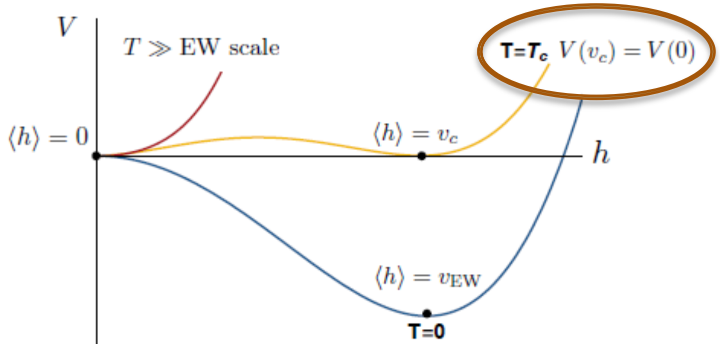


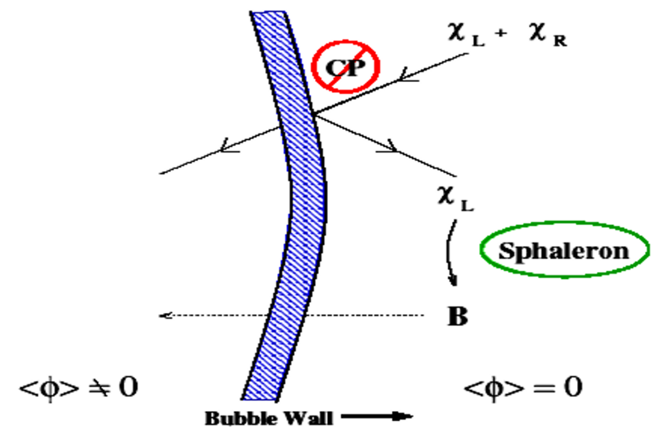


- Bubbles expand at near speed of light. Processes near the wall highly out of equilibrium **

Baryon Number generation at the EW phase transition

- Start with B=L=0 at T>Tc
- In a first order EW phase transition, universe tunnels from h = 0 to h≠0 vacuum via bubble nucleation.





- Particles flow into the expanding bubble wall and **CPV implies that the wall exerts different forces on particles and antiparticles creating a chiral asymmetry**

$$\sigma_{t_L \to t_R} \neq \sigma_{t_L^c \to t_R^c} \qquad \Delta \equiv n_{t_L} - n_{t_L^c} = -(n_{t_R} - n_{t_R^c}) \neq 0$$

- Outside the bubble, EW sphalerons allow a fraction "f" of the chiral asymmetry in quarks to be shared with leptons ➔ Sphalerons violate B+L, but conserve B-L ; Asymmetry in right-handed fields not touched by sphalerons

$$n_B - n_{\bar{B}} \propto \left[n_{t_R} - n_{t_R^c}\right] + (1-f)\left[n_{t_L} - n_{t_L^c}\right] = f\Delta$$

A net baryon asymmetry is generated this way

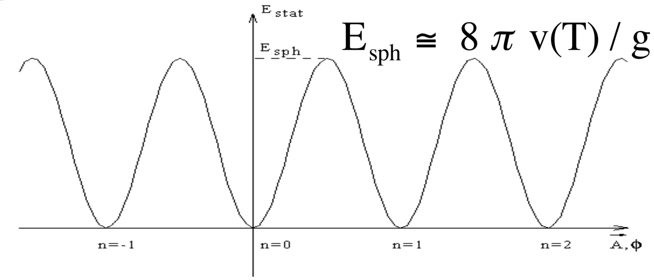
Baryon Number Violation at Finite Temperature

For a short period, EW sphalerons work to generate the desired baryon asymmetry;
Then need to shut off quickly to prevent washout.

- Sphaleron rate at high T are highly unsuppressed $\Gamma_{\Delta B \neq 0} \propto T$ (in equilibrium)
- At finite temperature, instead, Boltzman suppressed

$$\boxed{\Gamma_{\Delta B \neq 0} \cong \beta_0 \, T \exp(-E_{sph}(T)/T)}$$

$E_{sph} \cong 8\pi \, v(T)/g$



Baryon Asymmetry Preservation

if $n_B = 0$ at T > Tc, independently of the source of baryon asymmetry

$$\frac{n_B}{s} = \frac{n_B(T_c)}{s} \exp\underbrace{\left(-\frac{10^{16}}{T_c(\mathrm{GeV})} \exp\left(-\frac{E_{sph}(T_c)}{T_c} \right) \right)}_{<<1 \;\rightarrow\; v(T_c)/T_c \sim 1}$$

If $\Gamma_{\Delta B \neq 0} \lesssim H \sim T^2/M_{Pl}$ $\cancel{B}$ processes frozen

To preserve the baryon asymmetry demands a Strong First Order EWPT

Transition does not occur at Tc, but rather at Tn (bubble nucleation temp.) [Tn < Tc]
→actually transition from false vacuum to real one requires $S_{bounce}/Tn \sim 140$

EW Baryogenesis demands new Physics/ New Scalars

- EW Baryogenesis fails in the Standard Model:
  - Higgs boson too heavy ➔ crossover rather than strong first order EWPT
  - not sufficient CPV to generate required Baryon asymmetry

EW Baryogenesis demands new Physics/ New Scalars

- Simplest case: enhancing EWPT through Singlet extensions

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2 \quad +$$

- With Explicit Z2 breaking
- Z2-symmetry unbroken (at T=0)
- Spontaneously broken Z2

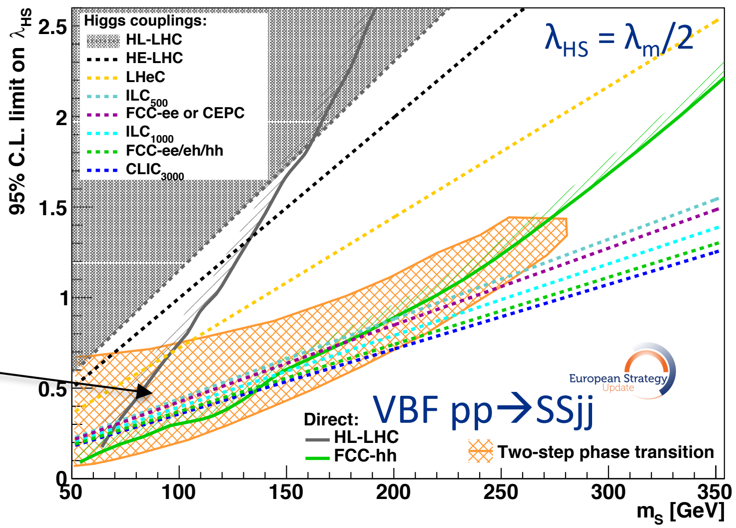
➔ Different thermal histories, with 1 or 2 step phase transitions and strong first order EWPT
- Important to check nucleation calculation -

➔ Rich phenomenology at Colliders: Higgs precision, Higgs trilinear coupling, double Higgs production, direct new scalar searches, possible effects of CPV

No H-S mixing: S stable

Case with Z2-symmetry preserved

Region with strong first order two step phase transition [(0,0)→(0,v_S)—>(v,0)], relevant for EWBG scenario can be probed by the full FCC or CLIC programmes

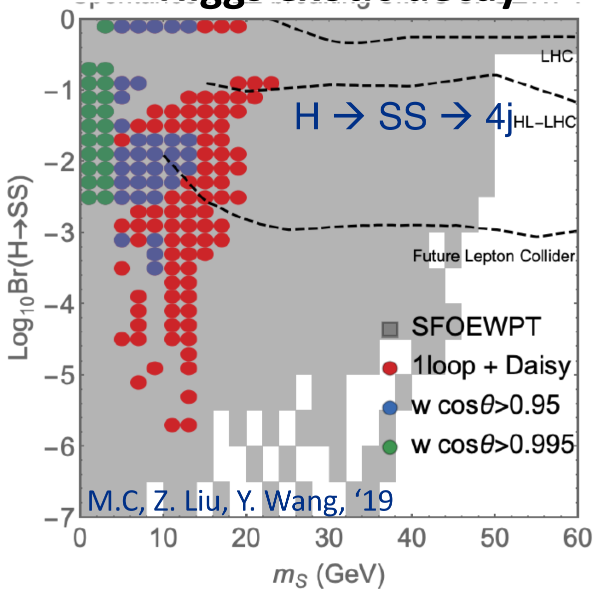


EW Baryogenesis demands new Physics/ New Scalars

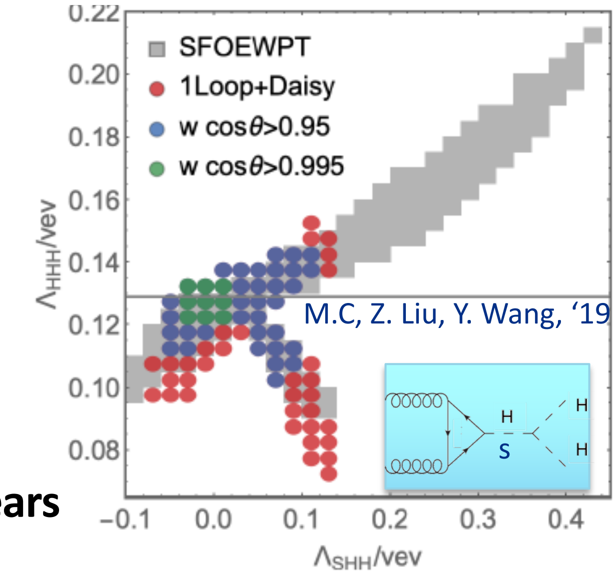
Spontaneously Broken Z2-symmetry

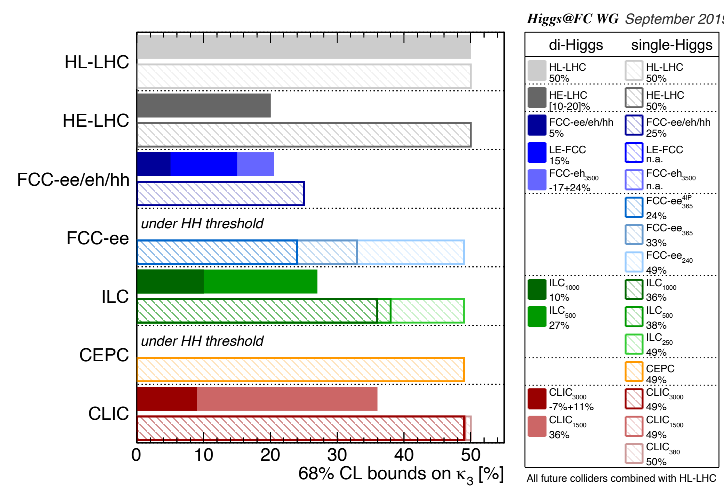
[In connection with a dark gauge symmetry, spontaneously broken by a dark Higgs vev.]

Higgs exotic decay



Higgs Trilinears





Other scenarios, with Z2 explicit breaking or in singlet SUSY extensions also provide interesting frameworks for EWBG @colliders

Thoughts/Questions

- WIMPS are still an excellent solution to the DM puzzle. The HL-LHC and next generation colliders (especially full FCC) have great potential in exploring WIMPs in uncharted territories.
  - How to exploit further the complementarity between collider and DD/ID experiments so that the latter inform/guide accelerator-based searches and vice-versa?

- New ideas/techniques and new experiments are rapidly evolving in searching for DM mediators, FIP's and LLP's at collider-based and accelerator-based exp., with important complementarities in the exploration of coupling strengths and masses.
  - How to coordinate those efforts in a compelling manner to maximized the extracted physical information?

- A new Forward Physics Facility (near the ATLAS IP) is being proposed, that will house a suite of exp. with new capabilities for Long Lived Particles, Neutrinos, Dark Sectors &QCD.
- An EOI for a Forward Multiparticle Spectrometer is being reviewed by CMS
  - Discussion of these opportunities and their level of maturity seems appropriate

Thoughts/Questions

Higgs physics exploration, through precision and direct searches of New Scalars opens opportunities to test models for EW Baryogenesis. It is exciting that many prospective future colliders (FCC, CLIC, ILC, CEPC) can put these ideas under strong scrutiny.

- How CP violation and flavor physics are best explored at the Energy Frontier?

If SUSY is a viable BSM theory, the Higgs mass value points towards gluino/stops masses in the few to tens of TEV region, at FCC-hh reach.

The possible Higgs degree of compositeness will be tested at the per mill level at full CLIC, FCC and ILC

- How can we better utilize that info to guide our BSM research?

Studies are advancing towards estimating a Muon Collider Higgs/BSM physics potential.

How can we better expand/scrutinize the ESG/PPG community studies for BSM reach at future lepton, ep and hadron colliders, with focus on their time scales and complementary physics gain?

Thank You !